Coastal Dynamics 2017
Paper No. 152

ASSESSMENT OF GREEN MEASURES AS COASTAL DEFENCES USING NUMERICAL MODELS

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Abstract

Climate change may reduce the performance and design life of “grey” coastal engineering interventions. Green solutions can be combined with present infrastructures providing extra flexibility to adapt our present beaches with affordable costs. This paper assesses the behaviour of a typology of green solutions (seagrass meadows) via numerical hydro-morphodynamic modelling for an erosive beach prone to episodic flooding, under typical Mediterranean conditions. A multivariate method for jointly assessing flooding and erosion via copulas is proposed and developed. In the considered pilot site, different layouts have been tested by analysing their efficiency and limits. It is concluded that, for moderate SLR rates (RCP 4.5. central trend), these green measures could attenuate efficiently the expected changes in marine drivers. However, the complexity of eco-hydraulic interactions on which the Nature Based Solutions depend would demand periodic monitoring and evaluation for maintaining acceptable risk levels, especially in the case of high-end scenarios.

Key words: flexible interventions, sea-grass meadows, morphodynamic impact, climate change, beach erosion and flooding

1. Introduction

Coasts are dynamic areas that foster growth in many societies by integrating several uses (e.g. tourism, fishing, aquaculture, maritime transport, etc.) that leave a severe anthropogenic footprint. Coastal infrastructures, including harbours, modulate the interactions of human uses with climate drivers and marine resources. Global warming consequences such as sea level rise (SLR), changes in wave patterns and storminess may alter the fragile coastal balance and hamper sustainable long-term coastal management.

Because of this, climate change impacts have received considerable attention for vulnerable systems like low-lying coasts (Sánchez-Arcilla et al, 2011). In the last years, a number of studies have addressed the effects of SLR on beaches (e.g. Luo et al, 2015; Monioudi et al, 2014; Revell et al, 2011; Sánchez-Arcilla et al, 2011), coastal defense structures (e.g. Burcharth et al, 2014; Isobe (2013)), coastal ecosystems (e.g. Kane et al, 2015), overtopping of port breakwaters (Sierra et al, 2016) or flooding of urban areas (e.g. Hallegatte et al, 2011; Paudel et al, 2015). Other studies have analyzed the impacts of climate change-driven shifts of wave patterns on beaches (e.g. Adams et al, 2011; Casas-Prat et al, 2016; Sierra and Casas-Prat, 2014; Zacharioudaki and Reeve, 2011) or on harbours (Casas-Prat and Sierra, 2010; 2012; Sierra et al, 2015). Recently, Sánchez-Arcilla et al. (2016b) assessed the combined impacts of SLR and changing wave patterns on ports.

To lessen climatic impacts on coastal areas, many studies have proposed adaptation measures (e.g. Anthoff et al, 2010; Hinkel et al, 2014; 2013; Klein et al, 2001; Linham and Nicholls, 2012; Moritz et al, 2015; Mycoo and Chadwick, 2012). Most of such proposed interventions are grey solutions that provide immediate adaptation but with high initial and long term maintenance costs (due to their rigidity). When the functionality needs of grey works are not met, their upgrading and substitution may become difficult due to technological limits and costs typical of rigid infrastructure.

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Nature based solutions can soften some of the drawbacks that grey infrastructures have particularly in the mid to long-term. They accommodate and damp hydrodynamic drivers with eco-hydraulic processes (e.g. Jones et al, 2012; Keijsers et al, 2015; Pontee et al, 2016; van Loon-Steensma (2015)). For example, vegetated areas such as sea-grass or wetlands reduce the length and height of incoming waves (e.g. Horstman et al, 2014; Möller (2006); Möller et al, 1999; Vuik et al, 2016), decrease surge heights (Möller et al, 2014) and function as a natural beach defence (e.g. Arkema et al, 2013; Borsje et al, 2011; Gedan et al, 2011; Temmerman et al, 2013; 2012). The joint application of structural engineering plus natural solutions such as vegetation may provide a plausible option for maintaining coastal resilience with affordable economic and energy costs. And yet, their quantitative behaviour remains poorly known, hampering their widespread use in coastal engineering.

Based on this, the paper deals with the performance and adaptation potential of such hybrid solutions for coastal protection and mitigation (i.e. carbon storage) against climate change. The proposed interventions are assessed for a stretch of the Spanish Mediterranean coast, using simulations from numerical models validated for the area. The required vegetation parameterizations come from a set of large scale wave flume tests. The analysis is based on the dynamics of an urban beach (Badalona beach, near Barcelona, figure 1) which has become artificial for the present coastal situation. It, thus, requires permanent maintenance and here nature-based-solutions (NBS) could offer an interesting alternative, provided their behaviour and deployment criteria are well established and accepted by the community.

This contribution, whose main aim is to improve the available knowledge for such NBS, is structured as follows. Section 2 describes the methodology, with emphasis on the modelling tools and hydrodynamic scenarios. Section 3 assesses the performance of the proposed green interventions, whose behaviour is discussed in Section 4. Section 5 presents some preliminary conclusions.

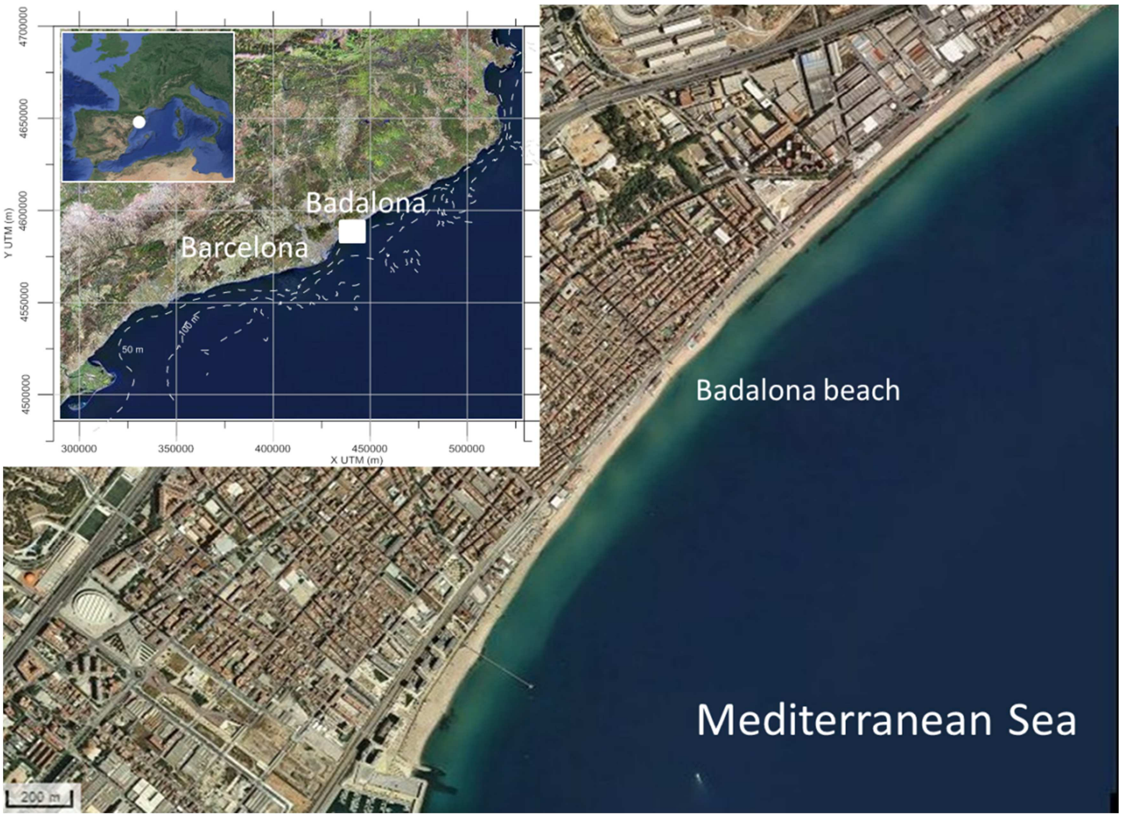

Figure 1. Study area (Catalan coast, NW Mediterranean Sea) indicating the location of Badalona beach, the selected case study

2. Methodology for a Mediterranean-type beach

2.1. *Climate change in the NW Mediterranean coast*

IPCC-AR5 maps of SLR for the Mediterranean Sea (IPCC, 2013) project an increase slightly inferior to the global mean, with a reduction of around 10%. Hence, the following projections by the end of the century have been assumed: 0.47 m for RCP 4.5 and 0.88 m for RCP 8.5 scenarios. A high-end SLR scenario of 1.8 m has been also considered. This is due to the existence of studies (e.g. Mori et al, 2013) that suggest reaching a global SLR near 1.80 m. These studies indicate that a sharp increase of sea level is possible, with a low probability of occurrence (less than 5%), but non negligible (Jevrejeva et al, 2014).

The general trend in the Mediterranean shows a relative decrease in wave energy projections (Lionello et al, 2008), though when combined a with SLR increase this can generate either higher or lower coastal waves depending on the relative weight of shoaling, refraction and diffraction. These projections are similar to those of Casas-Prat and Sierra (2013) who found a general decrease of the median Hs in most of the NW Mediterranean, with local increases of this parameter in the Gulf of Genoa. The seasonal distribution of waves may also change, with greater median Hs in summer and lower in winter. Extreme events show a decrease in frequency, but may present an increase in intensity with changes in the seasonal distribution of directional sectors. This, in turn, can generate changes in sediment transport patterns and the state of dynamic equilibrium of many beaches.

2.2. *The selected pilot beach*

Badalona (figure 2) is a reflective urban beach with a seafront promenade in its backshore between +5 and +6 above MWL. This study case has coarse sand (for this coastal sector) that ranges from 350 to 600 μm. The main impacts reported in the recent past are severe shoreline retreat and flooding due to frequent run-up episodes. Despite the shoreline retreat (-1.3 m/yr, CIIRC, 2010), important sand volume accumulations happen at the backshore due to the impact of storms in conjunction with high water levels. Flooding and episodic erosion are thus, the present dominant processes in the selected coastal stretch (Sánchez-Arcilla et al, 2014).

This pilot beach is representative of low-lying squeezed urban beaches in highly touristic areas like the Mediterranean. They suffer from chronic sand scarcity (Sánchez-Arcilla et al, 2016a) and their present dysfunctional behaviour may get aggravated under future (higher) mean sea levels, where the frequency and intensity of erosion and flooding episodes is expected to increase. This may lead to resistant and functional failures of present coastal structures/interventions which, combined with the projected increases in coastal population (Hinkel et al, 2014) will result in higher social and economic vulnerability.

Figure 2. The back beach and sea-front promenade of Badalona beach.

2.3. *Proposed sequential methodology*

The storm impact on Badalona beach has been assessed with a locally adapted version of the XBEACH model (Roelvink et al, 2009), that solves nearshore hydrodynamics by coupling an action balance equation for waves (Booij et al, 1999) with a 2DH Navier-Stokes shallow water solver (Stelling and Duinmeijer, 2003). The circulation fields feed an advection-diffusion equation (Galapatti (1983)) to calculate sediment fluxes that are used on a sediment mass balance equation. The equilibrium concentration at the bottom uses van Rijn (2007) formula, whose performance at the Catalan coast has been calibrated and tested (Gracia et al, 2013; Sánchez-Arcilla et al, 2014). The effect that vegetation has on sea-swell and infragravity waves, including wave setup has been included with extra terms in the action balance (Suzuki et al, 2012) and momentum equations (van Rooijen et al, 2016).

The set of hydrodynamic scenarios considered is based on storms with an average duration of 24h that can be schematized by a trapezoidal distribution for the wave height (same growth and decay rates). This hypothesis can be considered as plausible according to the extreme wave climate analysis performed by Lin-Ye et al. (2016). Offshore sea level is kept as constant. Six storm return periods (1,5, 10, 25, 50 and 100 years) and three characteristic directions have been selected (E, ESE, SE). This is summarized in Table 1.

Table 1. Summary of all simulated beach configurations. The central blue box shows hydrodynamic scenario variables and values, the green boxes indicate the different seagrass meadow layouts and the white box stands for the present conditions used as a reference.

Seagrass Meadow (50 stems/m^2)

SLR (m)	RP (years)	Wave Dir (Mag. N)
0	1	E
0.2	5	ESE
0.5	10	SE
1.2	25	
1.4	50	
1.6	100	
1.8		

Seagrass Meadow (100 stems/m^2)

Present Conditions

Eustatic sea level is considered as constant throughout each simulation. Eight combinations of SLR plus storm surge have been considered (0 cm, 0.2 m, 0.5 m, 0.9 m, 1.2 m, 1.4 m, 1.6 m, 1.8 m). Because of the relative short time for the storm duration (24 hours), it is assumed that mean sea level remains stationary during the computations. Summarizing, 6 different return periods × 3 directional sectors considered × 8 SLR scenarios lead to 144 different hydrodynamic conditions for the analysis.

Flooding maps (flooding extension and water depth) and erosion maps (erosion extension and post-storm elevation) have been derived directly from the morphodynamic model outputs. Flooding consequences (random variable u in Equation 1, flooding costs in euros) are estimated from the XBEACH flooding output (flood extension and water depth) that acts as a predictor for a cost curve (flooding cost per m^2 vs. water depth at any computational cell from the emerged part). This curve has been obtained empirically by Velasco et al. (2016) for the Barcelona city, gathering data from local insurance companies and expert knowledge. The upper limit of this curve reaches 300 euros/m^2 for water depths near 2 m.

The accumulated sand volume (random variable v in Equation 2, accumulated volume in m^3 distinguishing between deposition and erosion) and the losses due to flooding have been computed for each simulation, comprising two samples of 432 values each, because three layouts have been tested (144 hydrodynamic scenarios × 3 layouts = 432 values for flooding cost and erosion, respectively). The three layouts are: 1) present condition; 2) seagrass meadow between the -4 and -6 meters with a stem density of

50 stems/m^2; 3) same as 2) but with a stem density of 100 stems/m^2.

The two selected impact variables (u and v) are treated as random and have been fitted to a Gumbel distribution (Equation 1) and a reverse Gumbel distribution (Equation 2), respectively. Because of the different features of the performed simulations (each one has different drivers and layouts), their location ($\mu1$, $\mu2$) and scale parameters ($\sigma1$, $\sigma2$) have been estimated using a generalized linear model (GLM) (Rigby and Stasinopoulos (2005), Yee and Stephenson (2007)). This assumption leads to two marginal distributions that facilitate the comparisons for a given scenario (e.g. hazard) with a set of constraints (see figure 3).

$$f\left(u \mid \mu_1\left(Alt, H_{s,p}, SLR, \theta_{wave,p}\right), \sigma_1\left(Alt, H_{s,p}, \theta_{wave,p}\right)\right) = \frac{1}{\sigma_1} \exp\left\{\left(\frac{u-\mu_1}{\sigma_1}\right) - \exp\left(-\frac{u-\mu_1}{\sigma_1}\right)\right\}$$

(1)

$$f\left(v \mid \mu_2\left(Alt, H_{s,p}, SLR, \theta_{wave,p}\right), \sigma_2\left(Alt, H_{s,p}, \theta_{wave,p}\right)\right) = \frac{1}{\sigma_2} \exp\left\{\left(-\frac{v-\mu_2}{\sigma_2}\right) - \exp\left(-\frac{v-\mu_2}{\sigma_2}\right)\right\}$$

(2)

where Hs,p is the significant wave height at the peak of the storm at deep water (in meters), SLR is the prescribed sea level rise (in meters) and θwave,p is wave direction (at deep water) at the peak of the storm. “Alt” corresponds to a categorical variable that is equal to 0 for the reference case; 1 for the 50 stems/m^2 case and 2 for the 100 stems/m^2.

There should exist a relationship between sand accumulation and flood losses, especially at the upper tail of the marginal distributions (extreme flooding costs are associated with extreme hydrodynamic conditions that also induce severe erosion). Hence, any risk assessment needs to consider a joint probability distribution function (jpdf) so as to cover erosion and flooding in a combined manner. The dependence structure for both marginal distributions (Eq. 1 and 2) is based on a Gumbel copula function (Equation 3) that belongs to a family of copulas suitable for upper tail dependence. The only free parameter of such copulas is an association parameter (θ). As it has been done for the marginals (Equations**1 and 2), this parameter has been considered in terms of an additional GLM that depends on SLR. That assumes that the two marginal distributions do not have a constant dependence, but rather that it grows linearly as SLR increases. That implies that with low SLR, the flood and accumulation losses can be more heterogeneous (i.e. it would be possible to have relevant accumulation, but minor flood losses or vice versa), whilst high SLR implies a more homogenous behaviour (i.e. both important accumulation and flood losses). This dependence structure is considered to be more realistic for simulating random samples. All the covariates (Hs,p, SLR, θwave,p) for the set ($\mu1$,$\sigma1$, $\mu2$,$\sigma2$,θ) are statistically significant. A state-of-the-art maximum likelihood estimator has been used for fitting the GLMs (Equation 3). Other upper-tail dependence structures (e.g. Clayton (1978) and Joe (2014)) have been tested, but they presented higher values of AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion), while the target was to achieve low values of both AIC and BIC criteria, indicating a better fit.

$$C\left(u, v; \theta(SLR)\right) = \exp\left[-\left\{\left(-\log u\right)^{\theta} + \left(-\log v\right)^{\theta}\right\}^{1/\theta}\right] \qquad (3)$$

Assuming GLMs rather than constant values for the set of parameters ($\mu1$,$\sigma1$, $\mu2$,$\sigma2$,θ) should therefore help quantifying the aggregated impacts of extreme waves and sea levels. This should provide a more complete estimation of impacts and intervention performance.

3. Analysis of green coastal interventions

3.1. *Nature Based Solutions*

An alternative (inspired on Nature as observed in many Mediterranean coastal tracts) to dampen hydrodynamic drivers for any given beach and to favor accretive behaviour, can be an alongshore meadow of sea grass. The proposed vegetation field should span from 4 m to 6 m water depth with a mean cross-shore width of 180 meters and an alongshore extension of 2.2 km (area enclosed within the green contour in figure 3). These dimensions have been derived from neighboring beach meadows (natural) together with practical criteria for coastal interventions based on local experience.

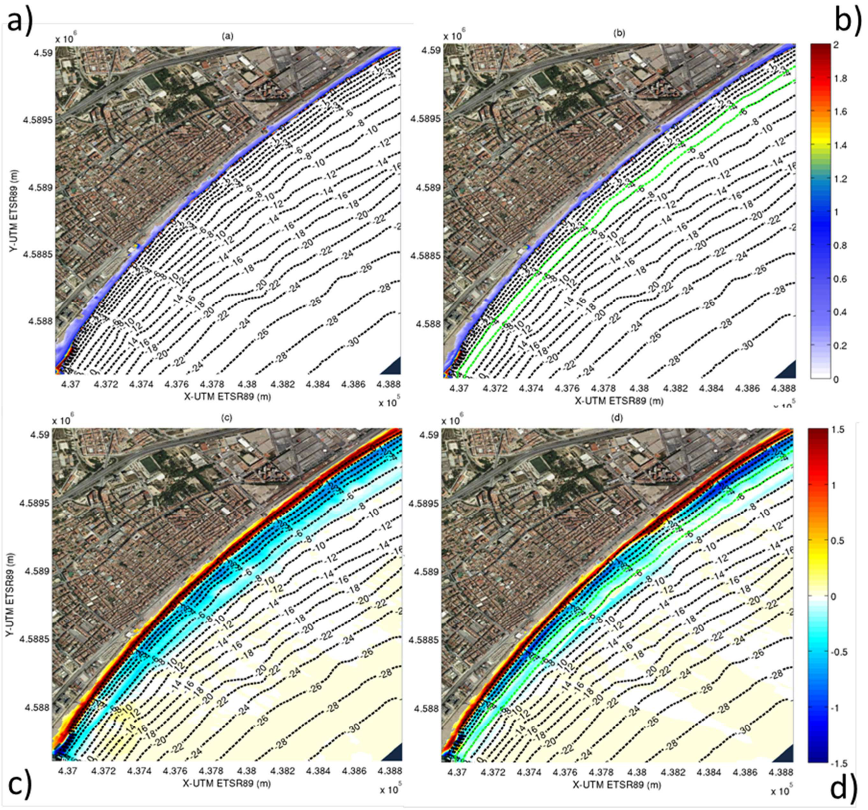

Figure 3. Flooded area and sand accumulation/erosion patterns at the Badalona beach produced by a wave storm of 5.1 m (5-year return period) and a SLR of 1.2 m. Panels a and b: flooded area represented by the coloured scale that indicates the water depth in meters: (a) baseline case and (b) baseline plus vegetated area (100 stems/m^2, with green dots limiting the vegetated zone). Panels c and d: sediment morphodynamic evolution in blue, erosion and in red accumulation. All colour scales are in meters. The isobaths represent pre-storm conditions.

Two different vegetation densities are proposed: 50 stems per m^2 (Alternative 1 or A1) and 100 stems per m^2 (Alternative 2 or A2). The stem height is considered to be 0.5 meters. The density of stems is assumed to be spatially uniform for each selected case. The proposed stem heights and densities reproduce sea grass meadows that have existed in the vicinity (e.g. *Posidonia Oceanica*) and have been tested in large-scale hydraulic experiments in the Barcelona CIEM flume (Sanchez-Arcilla and Cáceres, 2017).

The effect of these meadows can be explained via two natural processes: (i) wave attenuation due to the flexible damping of sea-grass stems that diminishes hydrodynamic gradients; and (ii) a more heterogeneous sand redistribution within the active profile, that leads to local sand accumulations.

3.2. *Quantitative performance (numerical simulations)*

The simulated cases are summarized in figure 3 and Table 1. The behaviour of the Badalona beach after the selected storm events shows (figure 3) the different evolution depending on whether or not vegetation was present. The performed morphodynamic simulations indicate a reshaping of beach profiles which results in sand overwashing and therefore accumulation in the back beach, together with erosion in the upper part of the foreshore and down to the closure depth (about 6.35 m, CIIRC(2010)) of the active profile. This behaviour, typical of steep beaches from semi-enclosed areas with limited swell like the Mediterranean, requires treating the erosion volume in homogeneous subdomains, so that the observed shoreline retreat is not masked by the balancing erosion and deposition volumes.

The maximum water depth and flooding extension are lower with a sea-grass meadow in front of the beach, especially at the center and southern part of the domain (figure 3a-b). Lower sand accumulations also appear at the same area, highlighting the added resistance of the sea-grass patch. Note also (figure 3d), that erosion is significantly lower within the vegetated zone. In (figure 3c) the non-vegetated post-storm pattern is more homogeneous with erosion and accumulation rates steadier along a given isobath.

The two main scenarios considered to assess vulnerability (i.e. losses or consequences of the acting hydrodynamic drivers) have been presented already in Table 1. The resulting joint probabilities of exceeding locally suitable thresholds for flooding and erosion (figure 4) show a highly vulnerable response for SLR above 1.0 m and for significant wave heights above 5.0 m. The sharp increases in the joint probabilities (accumulated) of occurrence depend, as expected, on the combination of drivers (Hs, MSL and direction) for a given beach configuration. This methodology can thus provide a “quick-scan” of the overall state of a beach given a wide range of hydrodynamic conditions. This first approximation can serve the needs of decision makers that require a timely first assessment. Despite high resolution models providing more accurate information, the computational cost and prediction time may become unacceptable, especially under disaster risk management while these data-driven analytical formulations can deliver first guidance to decide whether or not interventions are necessary under a forecasted natural disaster. The projected behaviours feature both mid-range losses (the joint probability of reaching accretion volumes up to 10000 m^3 and losses due to flooding up to half-million euros) and high range losses (the same but with volumes up to 15000 m^3 and losses up to 1 million euros).

The reason for dealing with erosion/accretion impacts in volumetric terms while flooding is assessed in monetary units (as befits a conventional estimation of vulnerability) is that these variables capture better the differential response of the beach (and thus, the different vulnerability) for the two processes (erosion or inundation). In general terms both A1 and A2 configurations outperform the A0 case (figure 4) with almost all hydrodynamic conditions. The difference is more evident with waves corresponding to a return periods of 5 years rather than for milder waves (figure 4). With a 1-year return period storm (Hs near 3.5 m), the results show a limited effect of sea-grass which in this case offers only marginal protection (A0 may even perform better than A1/A2 due to the absence of any significant sediment redistribution). This becomes more clear under a higher mean-sea level, where the damping of limited length stems becomes progressively lower. The combination of erosion/accretion with flooding also shows how the spatial inhomogeneity produced by sea-grass patches may lead to a post-storm geometry where locally flooding may be enhanced, resulting in higher combined impacts with vegetation.

The main effect of adopting more hazardous scenarios is to translate the probabilities along the x-axis leading thus to higher impacts for any given hydrodynamic setting. Note also that high losses for a moderate storm require a high SLR (up to 2 m in figure 4). However, the probability is almost unity when considering higher waves and 1.75 m of SLR (figure 4). This corresponds to a mean sea level projection that although unlikely (Jevrejeva et al., 2014), remains plausible.

The obtained results show that a plant canopy can diminish losses with high storms (4.5 to 7 m of significant wave height), but their performance is not as good as that for milder events (2.5 to 4.5 m). The obtained wave attenuation vs. water depth relationship shows that lower SLR rates lead to lower impact probabilities (less than 0.2), even for storms with wave heights near 6 m (more than 10 year return period). Finally, the distance in impact “space” between the A0 and A1-A2 cases increases in the lower SLR range. Therefore, the proposed meadow can increase coastal resilience in a practical set of scenarios, though it performs better with moderate SLR.

Numerical results have shown how green interventions can reduce sediment mobility (in terms of volumetric accumulation in erosive or depositional areas) and the losses induced by flooding for a typical anthropically conditioned beach in the Mediterranean. The combined vulnerability reduction is associated to the damping exerted by eco-hydraulic processes generated by the vegetation meadow on the incident wave and current fields. Here the total area occupied by plants is not critical, once the sea grass meadow exceeds a minimum threshold area. The meadow density also plays a role, where it has been shown that the A2 configuration (100 stems/m^2) is better suited for damping the acting hydrodynamics than the A1 case (50 stems/m^2). This coincides from previous numerical simulations for another Mediterranean beach with similar conditions (Sánchez-Arcilla et al, 2015).

The analysis of lower risk scenarios confirms that the sea grass meadow always performs better for the lower range of sea level rise. For a SLR of 0.9 meters and a storm of significant wave height equal to 6.0 meters the hazard probability almost reaches the 0.4 level (Figure 4(c)) without vegetation while the corresponding hazard with seagrass (for the same area) goes down to an almost 0 value according to the performed simulations. However, for a sea level rise of 1.2 meters (Figure 4(f)) and the same significant wave height (6.0 m), the probability is 0.7 at the reference state (blue) but about 0.4 with seagrass meadows (green and orange). In other words, the efficiency of the meadow decreases as sea level increases, reflecting the importance of the free board above the stem length, a result in accordance with the available knowledge for submerged breakwaters where the importance of the crest level freeboard is also paramount. In any case for moderate rates of sea level rise, the sea grass protection reduces considerably the hazard even for extreme (for the Mediterranean) wave heights of order 6.0 meters.

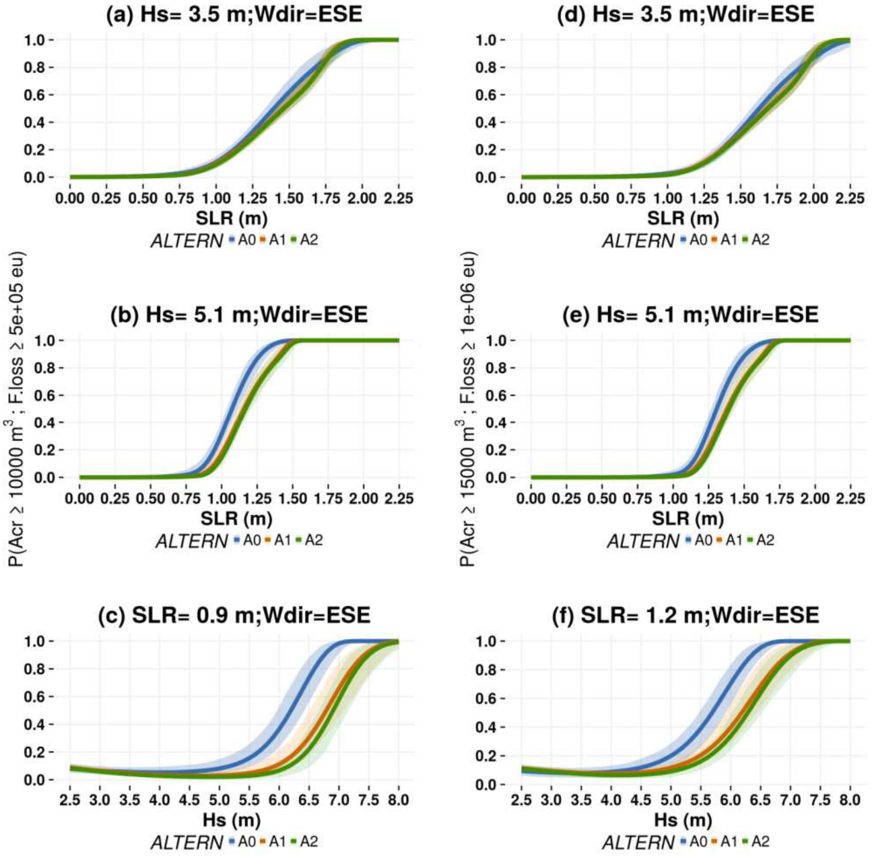

Figure 4. Joint probability of exceeding a certain flooding cost (F.loss, in euros) and sand accumulation (Acr, in m3). Figures (a), (b) and (c):: mid-level conditions, figures (d), € and (f) high end scenarios. The sensitivity to the two main variables (SLR and wave height during the storm peak) becomes apparent in the obtained plots. Alternative 0 (blue) is no intervention; Alternative 1 (orange), is a seagrass meadow with 50 stems/m2 and Alternative 2 (green) same as A1

but with 100 stems/m2. The 95% confidence interval bands are shown with the same colours as the central distributions.

A flexible complement to the proposed sea grass patches can be submerged geotextile bags that are biodegradable and can provide an extra protection for a limited life time (Sánchez-Arcilla et al, 2016a). The extra sheltering offered by such flexible submerged barriers can help to diminish the stress on the sea grass during the early implementation stages, thereby increasing their chances of survival. The combination of the two flexible interventions can still be considered a green solution for maintaining acceptable risk levels and allowing the flexibility to adjust them for varying future climates.

Green solutions such as the ones here proposed require a periodic evaluation of their performance. Their flexibility adds a new uncertainty layer, not only in the design, but also in the maintenance phase. In-situ and remote monitoring can help to measure relevant indicators such as biota stress and growth levels, meteoceanographic drivers or water quality and turbidity. This information can serve to redefine these flexible interventions following climatic evolution. Forecasts from coastal early warning systems can also help to determine when further additional measures are required. Hence, “working with nature solutions” will require a long-term proactive plan that includes constant monitoring.

4. Conclusions

This study has shown via numerical modelling that nature-based solutions can help to diminish coastal hazards under climate change scenarios. The performance of such flexible interventions has been numerically analyzed for an erosive beach prone to episodic flooding in the Mediterranean. Episodic flooding and erosion have been assessed jointly based on a non-stationary Gumbel copula, providing a more robust tool than what would be obtained from independent assessments. The required hydrodynamic attenuation provided by submerged meadows has been parameterized with a unique set of large-scale flume data, where the eco-hydraulic damping process has been simulated with hydraulic tests under controlled conditions and minimum scale distortion.

In all the considered cases, better performance is found with moderate SLR (RCP 4.5. central trend), because the ratio stem height/water depth is higher. However, vegetation patches may lead to a spatially heterogeneous post-storm morphodynamic signature, with higher gradients than for the case without plants, which can lead to local areas with enhanced flooding impacts. This effect is more likely with moderate storms (return period of 1 year) and extreme SLR rates (1.75 m by 2100). Higher vegetation densities have been shown to perform better while the horizontal area is not critical above a threshold. These differences tend to diminish for high-end scenarios.

Acknowledgements

This article has been supported by the EU-projects RISES-AM (FP7-ENV-603396) and from the EU Horizon 2020 Hydralab+ project (No. 654110) plus the Spanish national project PLAN-WAVE (CTM2013-45141-R). We would also like to thank the Secretary of Universities and Research of the Department of Economics of the Catalan Generalitat (Ref. 2014SGR1253). The second author acknowledges the PhD scholarship from the Government of Catalonia (DGR FI-AGAUR-14).

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